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Glacial Meltwater Input to the Alaska Coastal Current: Evidence From Oxygen Isotope Measurements

GEORGE W. KIPPHUT[1]

Institute of Marine Science, University of Alaska Fairbanks

Results of a study of the oxygen isotopic composition of coastal, pelagic, and fresh waters from the northern Gulf of Alaska region are presented. This study was undertaken to investigate whether isotopic tracers could be of use in determining the important freshwater inputs to the Alaska Coastal Current (ACC) and whether they could confirm the presence of the ACC in coastal waters west of Kodiak Island. The Alaska Coastal Current, the major coastal circulation feature of the northern Gulf of Alaska, can be distinguished from oceanic waters on the basis of its lower salinity at least as far west as Kodiak Island. This study adds significantly to the small amount of oxygen isotopic information available for the waters of this region. The isotopic results suggest that in late summer, glacial meltwater may provide a substantial portion of the total freshwater runoff into the ACC, and that the ACC does extend as far to the west as Unimak Pass.

INTRODUCTION

The Alaska Coastal Current (ACC) is the major coastal circulation feature of the northern Gulf of Alaska |*Schumacher and Reed*, 1980; *Royer*, 1981|. The ACC is a narrow (<30 km), high speed (20 to >175 cm/s) jet which is driven by freshwater discharge and winds. This coastal jet can be easily identified as a distinct feature from the vicinity of the Copper River (145°W) at least as far west as Kodiak Island. There is some suggestion that the ACC may be influenced by freshwater discharge originating in southeast Alaska |*Royer*, 1981|. The ACC can be distinguished from the larger, slower moving Alaska Current in the north central Gulf of Alaska by its lower salinity (Figure 1). The transport of the ACC can exceed 1×10^6 m^3/s and varies seasonally in response to fluctuations in freshwater runoff into the coastal zone |*Royer*, 1982|. Very high annual rates of precipitation in the coastal mountains which border the northeast Gulf of Alaska produce a large freshwater discharge which is at a maximum in early autumn and at a minimum in late winter.

The flow of the ACC west of Kodiak Island is less easily identified. Freshwater runoff decreases along the Alaska Peninsula, and the ACC can no longer be clearly distinguished on the basis of salinity alone. Indirect evidence suggests that at least some ACC water may flow as far west as Unimak Pass and that coastal waters may be transported northward through the pass into the southeastern Bering Sea. *Schumacher et al.* |1982| and *Schumacher and Reed* |1986| have used current meter and bottom pressure measurements to infer that westward coastal flow is present along the Alaska Peninsula and in Unimak Pass. Presumably, this flow is an extension of the ACC. However, it was not possible to estimate what fraction of the transport of the ACC reaches Unimak Pass relative to the more clearly defined transport of the ACC in the north central Gulf of Alaska.

Variability in the trajectory and transport of the ACC has implications for the biological and geochemical regimes of coastal and shelf waters in the Gulf of Alaska |*Reeburgh and Kipphut*, 1986|. Large, turbulent eddies have been observed in sections of the ACC |*Ahlnäs et al.*, 1987|, and the ACC is likely to be important in determining the distribution of suspended sediments |*Feely et al.* 1979; *Ahlnäs et al.*, 1987| and plankton |*Cooney*, 1986| in coastal waters. Variability in flow of the ACC is also important in regulating across-shelf mixing processes |*Johnson et al.*, 1988|.

In this study, results of a preliminary survey of oxygen isotopic composition of coastal, pelagic, and fresh waters from the northern Gulf of Alaska region are presented. This study adds significantly to the isotopic data set for this region. The oxygen isotope measurements suggest that in late summer, glacial meltwater may provide a substantial portion of the total freshwater runoff into the ACC, and that the ACC does extend as far to the west as Unimak Pass.

APPROACH AND METHODOLOGY

The $H_2{}^{18}O/H_2{}^{16}O$ ratio in seawater shows only slight variation except near those coastal margins where there is significant input or removal of fresh water. Precipitation is generally depleted in the heavier isotopes of oxygen because of isotopic fractionation processes which occur during evaporation and condensation. The fractionation processes are temperature dependent, with the result that precipitation at higher latitudes and higher elevations shows a progressively lower $H_2{}^{18}O/H_2{}^{16}O$ ratio |*Siegenthaler and Oeschger*, 1980|.

The oxygen isotope composition of coastal waters has been successfully used to distinguish circulation features involving waters of different $H_2{}^{18}O/H_2{}^{16}O$ ratios. This method is attractive because the $H_2{}^{18}O/H_2{}^{16}O$ ratio is a

[1]Now at Center for Great Lakes Studies, University of Wisconsin-Milwaukee.

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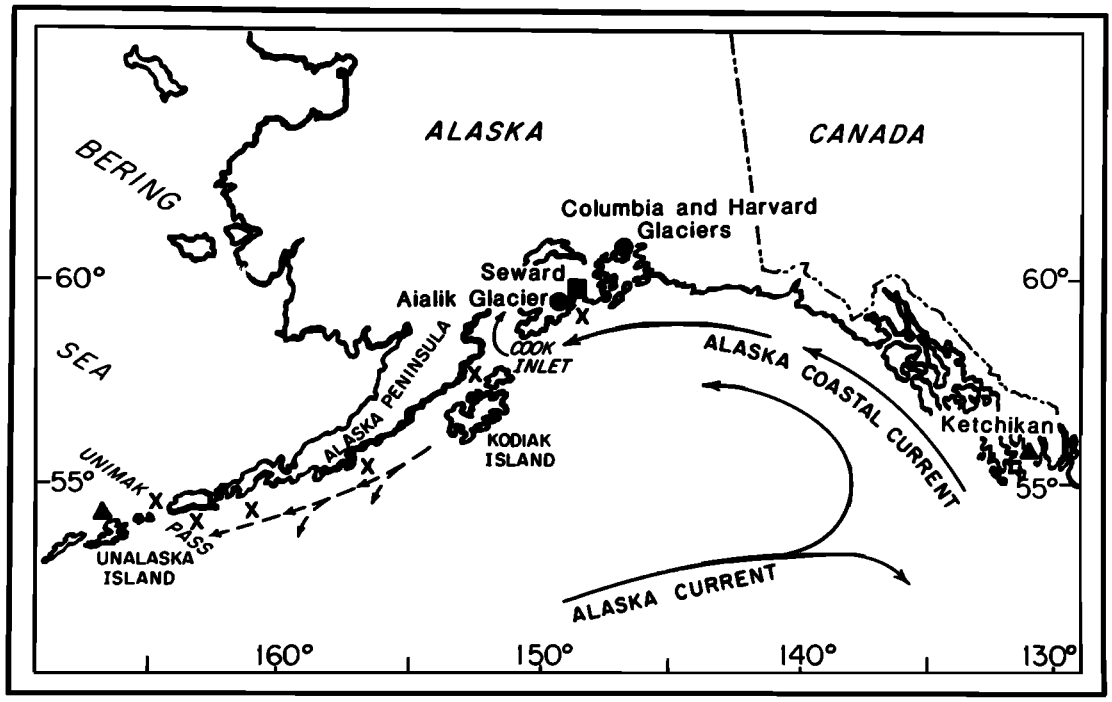

Fig. 1. Representation of the general circulation features of the northern Gulf of Alaska. The Alaska Coastal Current is driven by wind and the large amounts of freshwater runoff from the coastal mountains of southeast and south central Alaska. The trajectory and transport of the ACC west of Kodiak is not well known (dashed lines). Oxygen isotope sample locations are shown for coastal precipitation (triangles), glacier ice (circles), and coastal marine waters (crosses).

conservative property of water, and when combined with measurements of salinity, $H_2{}^{18}O/H_2{}^{16}O$ ratios may be useful in determining distinct components of water masses. Mixing and other physical processes which change the salinity of a water mass will also change its $H_2{}^{18}O/H_2{}^{16}O$ ratio. Because of the temperature effect on isotopic composition, this method is can be particularly useful in higher-latitude regions. Successful applications include deduction of ice melt inputs to coastal waters [*Tan and Strain*, 1980; *Bedard et al.*, 1981; *Redfield and Friedman*, 1969], and determination source waters in the New York Bight and Gulf of Maine [*Fairbanks*, 1982; *Chapman et al.*, 1986].

In this study, samples were collected from environments which included coastal waters, glacial ice, offshore Gulf of Alaska surface waters, and coastal precipitation. The intention was to characterize the isotopic composition of potential source waters of the ACC. Some of the sample locations are shown in Figure 1. Coastal seawater samples were collected during a transit from Seward to Unimak Pass aboard the R/V *Alpha Helix* in September 1982. Offshore waters were collected at various seasons during a number of cruises of the R/V *Alpha Helix*. Glacial ice was collected by colleagues at a number of coastal locations in south central Alaska. Ice was collected from large bergs which had recently calved from the glacier face (Harvard and Columbia glaciers), or directly from the face of the glacier (Aialik Glacier). Physical settings for each of the three glaciers are described by *Field* [1975].

Oxygen isotopic composition of the water samples was determined by the Quaternary Research Center of the University of Washington and by Coastal Science Laboratories, Inc., of Austin, Texas. Both laboratories used methods in which the water sample is equilibrated with CO_2 gas and the isotopic composition of the gas is measured with a mass spectrometer. Duplicate aliquots of a number of water samples were analyzed by both laboratories to insure that results were comparable.

The $H_2{}^{18}O/H_2{}^{16}O$ ratio of the water sample is expressed as the fractional difference between ratios of the sample and a standard reference:

$$\delta^{18}O(‰) = \frac{H_2{}^{18}O/H_2{}^{16}O_{sample} - H_2{}^{18}O/H_2{}^{16}O_{SMOW}}{H_2{}^{18}O/H_2{}^{16}O_{SMOW}} \times 1000 \quad (1)$$

where SMOW is the $H_2{}^{18}O/H_2{}^{16}O$ of standard mean ocean water [*Craig*, 1961]. Analyses of duplicate samples indicated that precision was approximately 0.1‰.

Results and Discussion

The oxygen isotope-salinity relationship for the six samples from coastal waters is shown in Figure 2. In moving from left to right on this plot, one moves geographically from south central Alaska (directly south of Seward), to the southwest and Unimak Pass (Figure 1). The samples were collected during a 3-day period and represent as near synoptic a sampling of these coastal waters as is practical. Better coverage in the 28-30‰ salinity range would certainly be desirable, but oxygen isotopic composition and salinity are highly correlated in the region covered by these samples. One explanation is that these coastal waters are a mixture of only two major components, which have different salinities and isotopic compositions. The regression statistics which accompany Figure 2 can be

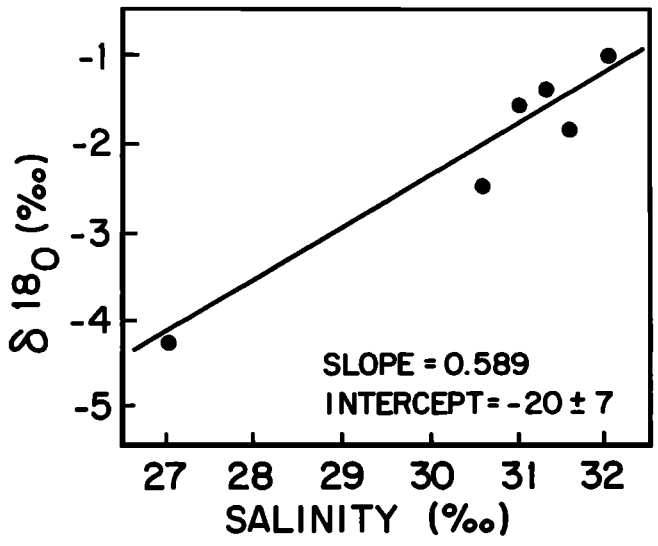

Fig. 2. Oxygen isotope salinity relationship for coastal waters between south central Alaska and the southeast Bering Sea. The regression is significant at $p<0.01$, degrees of freedom = 4, $R^2 = 0.94$

used to estimate the $\delta^{18}O$ of the two components. The $\delta^{18}O$ of the freshwater component is estimated from the zero-salinity intercept, which is approximately -20‰. If the high salinity component is presumed to be saline Gulf of Alaska water, which has a salinity of 32-33‰, then the data of Figure 2 indicate that the $\delta^{18}O$ of this component is approximately -1 to -2‰.

In Table 1, oxygen isotopic compositions of the glacial ice and coastal precipitation samples are presented. The precipitation samples from southeast and southwest Alaska were rain and snow collected at sea level, and they are not particularly depleted in $\delta^{18}O$. Ice from the Aialik Glacier, a relatively small, low altitude (1500 m) glacier in the Kenai mountains of south central Alaska, is also not very depleted

TABLE 1 Oxygen Isotopic Composition of Coastal Waters, Glacial Ice, and Precipitation at Locations Around the Margin of the Northern Gulf of Alaska

Location	$\delta^{18}O$, ‰	S, ‰
Coastal Marine Waters		
59.52°N, 149.70°W	-4.29	26.96
57.98°N, 153.94°W	-2.55	30.62
56.85°N, 156.07°W	-1.54	31.07
55.42°N, 160.81°W	-1.46	31.32
54.42°N, 164.24°W	-1.87	31.63
54.00°N, 166.96°W	-1.08	32.42
Coastal Precipitation		
Ketchikan (snow)	-11.7	
Ketchikan (stream)	-13.9	
Unalaska (rain)	- 8.8	
Unalaska (stream)	-10.6	
Glacier Ice		
Columbia Glacier	-17.8	
Harvard Glacier	-22.6	
Aialik Glacier	- 2.9	

Sample locations are shown in Figure 1.

in $\delta^{18}O$. The freshwater samples showing the greatest depletion are ice from the Columbia and Harvard glaciers. The $\delta^{18}O$ of ice from these glaciers is close to the predicted $\delta^{18}O$ of the freshwater component of the ACC (Figure 2). Columbia and Harvard are the two largest glaciers of the coastal Chugach Range of south central Alaska. They are formed at high altitudes and terminate in Prince William Sound. More than 50% of the ice of the Columbia Glacier originates at altitudes greater than 2000 m, with some accumulation at altitudes as high as 4000 m |*Nielsen*, 1963|.

There are few other studies with which the isotopic results can be compared. There are no published oxygen isotope data for coastal marine waters of the Gulf of Alaska. *Hage et al.* |1975| reported an annual average $\delta^{18}O$ in precipitation for Adak Island (western Aleutians) of -9‰. This value is in good agreement with the isotope data reported here from Unalaska Island and Ketchikan (Table 1). All three are coastal sites where most of the precipitation falls as rain. *Hage et al.* |1975| also reported an annual average $\delta^{18}O$ in precipitation of -21‰ for Whitehorse, Yukon, which is in the precipitation shadow of the coastal mountains and is much colder than the coastal areas. Oxygen isotope data for very high elevations (5 km) on Mt. Logan (approximately 75 km from the northeast Gulf of Alaska) indicate $\delta^{18}O$ values in the range -26 to -31‰ |*Holdsworth et al.*, 1984|. The $H_2{}^{18}O/H_2{}^{16}O$ ratios measured for precipitation and glacier ice in this study thus compare favorably with the previous isotope results reported for the margins of the northern Gulf of Alaska. They are also in general agreement with the $\delta^{18}O$ values which would be predicted on the basis of latitude and temperature alone |*Siegenthaler and Oeschger*, 1980|. More importantly, they support the contention that $H_2{}^{18}O/H_2{}^{16}O$ ratios can be used in the Gulf of Alaska to distinguish runoff resulting from melting of large glaciers ($\delta^{18}O \approx -23‰$) from runoff resulting from precipitation falling either as rain or snow at low, coastal elevations ($\delta^{18}O \approx -10‰$).

The saline component of ACC water was predicted to have a $\delta^{18}O$ of approximately -1 to -2‰. Eight near-surface samples from offshore marine waters in the Gulf of Alaska have been analyzed. The results are shown in Table 2. The measured $\delta^{18}O$ values of these surface waters range from -1.5 to -2.4‰. Four subsurface (>1000 m) measurements suggest that the deeper waters of the Gulf of Alaska are of nearly uniform isotopic composition, at $\delta^{18}O \approx 1.2‰$. Thus it appears as if the measured $H_2{}^{18}O/H_2{}^{16}O$ ratios both of offshore Gulf of Alaska water and of glacial ice are consistent with the two source ratios which are predicted from the $\delta^{18}O$/salinity plot (Figure 2).

Taken by themselves, the isotope data suggest that the coastal waters in southwestern Alaska are derived from coastal waters in the south central Alaska area. The oxygen isotope evidence supports the conclusions of *Schumacher et al.* |1982| and *Schumacher and Reed* |1986| that the Alaska Coastal Current is a continuous feature of the coastal Gulf of Alaska and flows as far west as Unimak Pass. The total length of the ACC is thus more than 1500 km.

ESTIMATION OF MELTWATER INPUTS

The oxygen isotope data presented here are consistent with only two major components or sources of the coastal waters. Further, the isotope data suggest that much of the

TABLE 2. Oxygen Isotopic Composition for Pelagic Gulf of Alaska Waters

Location	$\delta^{18}O$, ‰	S, ‰
59.82°N, 148.83°W	-2.1	31.72
59.48°N, 147.83°W	-2.4	31.89
58.39°N, 148.08°W	-2.1	32.09
58.24°N, 147.94°W	-1.9	32.22
58.24°N, 147.94°W (1000 m)	-1.2	34.35
58.24°N, 147.94°W (1500 m)	-1.2	34.49
58.10°N, 147.79°W	-1.7	32.27
58.10°N, 147.79°W (120 m)	-1.5	33.35
56.46°N, 146.35°W	-1.7	32.52
56.46°N, 146.93°W	-1.6	32.67
56.46°N, 146.93°W (2700 m)	-1.3	34.65
56.46°N, 146.93°W (3700 m)	-1.2	34.70
56.42°N, 145.70°W	-1.9	32.66

Sample locations are to the east and southeast of Kodiak Island. Locations are listed in order of increasing distance from shore. All samples, except those indicated, are from near-surface waters (0–10 m).

freshwater component results from glacial ice melt. Since there is little glacial ice melt runoff in southwestern Alaska, this interpretation would imply that essentially all of the freshwater input to the ACC comes from southeast or south central Alaska. A strictly two-component model for the ACC cannot be entirely realistic. This model would require that there is no freshwater runoff into the coastal zone west of Kodiak Island, and that certainly is not true. However, the rate of precipitation |*Schumacher et al.*, 1982| and the drainage area decrease markedly west of Kodiak, so that the freshwater runoff in this region is likely to be small compared with that in southeastern or south central Alaska.

The oxygen isotope data can be used in a more quantitative manner to estimate the contribution of meltwater from large glaciers to runoff into the coastal waters. A simple isotopic mass balance can be constructed if it assumed that there are only two major components of the freshwater runoff: meltwater from large glaciers and summer precipitation. If these components have different isotopic compositions, then determination of the $\delta^{18}O$ of the total freshwater runoff will fix the proportion of each component. The apparent $\delta^{18}O$ of the fresh-water runoff component is approximately -20‰ (Figure 2). If large glaciers are assumed to have a $\delta^{18}O$ = -23‰ (as represented by the Harvard Glacier) and coastal summer rains are assumed to have a $\delta^{18}O$ = -10‰ (as represented by the average of Ketchikan and Unalaska precipitation), then glacial runoff must contribute 77% of the total freshwater component. This preliminary set of isotope data does not allow any of these values to be tightly constrained, so that there is considerable uncertainty in the estimate of the large glacier component. The uncertainty in the $\delta^{18}O$ of the total freshwater runoff (±7‰) imposes an uncertainty of a least 30% on the estimated large glacier component of runoff.

The oxygen isotope estimate of the relative proportions of glacier and precipitation inputs to coastal waters can be compared with an independent estimate of these proportions. *Royer* |1982| used a hydrology model based on precipitation and temperature to estimate total monthly freshwater runoff from the southeast and south central Alaska regions. The same model calculations have been extended to distinguish the meltwater and precipitation components (T. C. Royer, personal communication, 1987). Results for September 1982 and September 1983 are shown in Table 3. The proportions of glacial meltwater were computed to be 26% and 42% for 1982 and 1983, respectively. Although the preliminary set of isotope data presented here (which are for September 1982) suggest a somewhat larger glacial component, they do support Royer's estimate of a substantial glacial meltwater input during the late summer. September is the time of the year when freshwater runoff is at a maximum |*Royer*, 1982|.

TABLE 3. Estimates of Freshwater Runoff into Coastal Waters of the Gulf of Alaska

	Total Discharge, m^3/s	Meltwater Component, m^3/s
1982		
Southeast Alaska	21,781	6,469
South central Alaska	23,492	5,408
Total	45,273	11,877 (26%)
1983		
Southeast Alaska	22,051	5,112
South central Alaska	20,655	12,653
Total	42,706	17,765 (42%)

Total discharges and the meltwater components were computed using the model of *Royer* |1982|.

Seasonal measurements of $H_2{}^{18}O/H_2{}^{16}O$ ratios in transits of the ACC from Prince William Sound westward to Unimak Pass (particularly during periods of minimum and maximum freshwater runoff), could more tightly constrain these preliminary results and could lead to volumetric estimates of transport of fresh water by the ACC and to specific identification of freshwater sources.

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G. W. Kipphut, Center for Great Lakes Studies, University of Wisconsin-Milwaukee, Milwaukee, WI 53204.

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